COMPUTATIONAL BRITTLE FRACTURE USING SMOOTH PARTICLE HYDRODYNAMICS

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We are developing statistically based, brittle-fracture models and are implementing them into hydrocodes that can be used for designing systems with components of ceramics, glass, and/or other brittle materials. Because of the advantages it has simulating fracture, we are working primarily with the smooth particle hydrodynamics code SPHINX. We describe a new brittle fracture model that we have implemented into SPHINX. To illustrate the code's current capability, we have simulated a number of experiments. We discuss three of these simulations in this paper. The first experiment consists of a brittle steel sphere impacting a plate. The experimental sphere fragment patterns are compared to the calculations. The second experiment is a steel flyer plate in which the recovered steel target crack patterns are compared to the calculated crack patterns. We also briefly describe a simulation of a tungsten rod impacting a heavily confined alumina target, which has been recently reported on in detail.

INTRODUCTION

Brittle materials are used in many defense applications. Certain armors have ceramic elements, for example. Underground bunkers consist of rock and concrete, and windshields in trucks, jeeps, and helicopters are made of glass. Any hydrocode used in the design or in the performance assessment of systems like these must accurately model the strength and fracture properties of brittle materials. The results of a hydrocode simulation depend on several factors including the particular way its fracture model is implemented. In general, fracture models must be tailored to the type of code–Lagrangian, Eulerian, or smooth particle hydrodynamics (SPH)–so that physically realistic cracks result in the context of the code's numerical treatment. But even the same model, implemented into two hydrocodes of the same type but with different coding details, can produce different results.

Statistical fracture models should incorporate a number of features including 1) the introduction of a random distribution of flaws, 2) a differential equation for evolving the local damage variable, 3) formulas for degrading the material strength, for modifying the equation of state (EOS), and for relaxing the stress components of the damaged material, and 4) methods for producing and representing cracks in the computational mesh. All of these components are interdependent and must function in mutually compatible ways if the experiments are to be modeled accurately.

We have chosen to use the SPHINX hydrocode for the present studies. SPHINX is based on the smooth particle hydrodynamics (SPH) formalism, which has certain advantages over other methods for modeling fracture. For example, once the damage is calculated and the material properties degraded, SPH allows for the

natural insertion of voids. SPH offers several additional benefits. Unlike conventional Lagrangian techniques, SPH avoids mesh tangling and is therefore much more robust in its treatment of problems with large material distortions. In general, SPH is more computationally efficient than Eulerian codes, and it avoids advection problems, such as numerical diffusion. SPH does have its own set of problems including instabilities in tension[1].

To be useful as a design tool, a hydrocode, along with its material strength and fracture models must be able to predict a wide range of experiments. Many fracture models are able to simulate one-dimensional (1D) flyer plate experiments accurately, but are unable to predict multi-dimensional data. Some models are accurate for a restricted set of geometries and boundary and initial conditions, but not for others. Our goal, which we have not yet reached, is to provide a hydrocode-based design tool with a single model for the strength and fracture of brittle materials that will accurately simulate a wide range of experiments and real applications.

The SPHINX code is well documented[2] and includes several of a number of models that have been proposed to simulate dynamic brittle fracture[3–8]. We have applied SPHINX with its Cagnoux-Glenn model[7,8] to simulate the impacts of steel projectiles on glass[9–11]. The results of the simulations agreed reasonably well with the global data, such as depth of penetration and the measurements of the free surface velocity on the backside of the target, but we were unable to match finer details of the crack patterns. Nor were we able to predict other experiments with the model parameters that were successful in the glass-impact study.

THE FRACTURE MODEL

Benz and Asphaug (BA) developed two statistical fracture models[3,4]. We began our investigations of statistical fracture with the model described in their more recent work[4], but in the process of implementing and testing the model in SPHINX, we changed it to such an extent that it is no longer fair to attribute the result to the original authors. We shall simply refer to our version as the smooth particle hydrodynamics statistical fracture (SPHSF) model.

The most important differences between the SPHSF model and those published by BA are the ways we seed the flaws and assign the flaw strengths or threshold stress values at which the flaws initiate damage in their local particles. BA select flaw strengths as uniform intervals on the domain of the Weibull distribution function and assign the flaws to randomly selected particles. BA continue the process of assigning flaws to particles until every particle contains at least one flaw. In SPHSF, we begin with an empirical parameter that defines the average number of flaws per unit volume. We then calculate the number of flaws in each particle from a Poisson distribution using the particle volume and the average flaw density. We adopted the new approach to avoid having the final distribution of flaws depending

on the spatial resolution of the problem. (Although to spare computer memory, we typically limit the number of flaws in each particle to the ten weakest.)

In principle, once the flaws are seeded we could use any statistical distribution for assigning their strengths. However, we follow the precedent set by BA and use the Weibull distribution although we use a slightly different functional form. Details of our model have been recently presented[12].

A scalar damage variable D is defined for each particle as the fraction of its volume that is relieved of stress by the growing cracks.

Once we compute the damage, we have to couple it back to the material strength and hydrodynamics calculations. The current version of SPHINX allows us to scale the yield stress and/or shear modulus for each particle linearly between a value corresponding to the intact material and a value corresponding to the fully fractured material. In this work, we use a constant shear modulus and let the yield stress decrease linearly to zero as the damage increases from zero to one.

Finally, the codes must have a way to let the particles separate and form cracks and material fragments. Again, different researchers use different methods to achieve particle separation. If a particle is fully damaged (D = 1.0), BA exclude that particle from the SPH summations over the neighboring particles. This exclusion effectively disconnects the damaged particle from its neighbors.

Other methods have been used to produce crack structures. Randles and coworkers[5] disconnect their damaged particles by reducing the smoothing length h. To prevent adverse effects on the time step, they limit the reduction of h to 0.8 of its original value. SPHINX can use either of these two methods. When we use the sum exclusion method, we do so only when the sum of the pressures of the damaged particle and that of its neighbors is negative. This scheme allows damaged particles to resist compression but not tension.

STEEL SPHERE FRAGMENTATION

Experiments have been conducted of brittle steel spheres impacted into PMMA plates for a number of velocities and plate thicknesses[13]. Two x-ray positions downstream of the plate recorded the sphere fragment patterns. The x-ray was adjusted so that the plate did not appear in the x-ray. SPHINX 3D calculations of two of these experiments, for a 3.38 mm thick plate, were made using the model described above and an elastic-perfectly plastic material strength model. For a sphere velocity of 3.0 km/sec, the sphere remained intact in the experiment. The SPHSF model parameters were adjusted for this case so that the sphere had only a small amount of surface damage. The 4.57 km/sec experiment was then simulated. The data and calculated sphere fragment patterns are shown in Figures 1 and 2 (not to scale) for the second x-ray position. The diameter of the experimental debris pattern was 46 mm and the calculated diameter was 42.8 mm. As can be seen from Fig. 2, the calculated pattern has an umbrella shape, whereas the data is planar. Interestingly, for a thicker plate (11.23 mm), the data was umbrella shaped. Grady estimates that the sphere broke up into about 440 fragments. In the SPHINX

calculations, there were only 1648 particles in the sphere, so calculations with more resolution are needed. These calculations are underway.

Fig. 1. Experimental sphere fragment

pattern.

Fig. 2. Calculated fragment pattern.

SPALL IN STEEL PLATES

Mock and Holt conducted a series of experiments in which they shot a steel flyer plate at a steel target plate[14]. The target was recovered and sectioned so that the pattern of spall cracks is visible. The experiments were conducted at four velocities and for two different steel heat treatments. SPHINX has no model to account for the heat treatment, but experiments for one heat treatment and two velocities were simulated. The SPHINX model for these calculations used the Cagnoux-Glenn damage model with a $\pm$ 10% random variation in the threshold stress for the start of damage. The Johnson-Cook material strength model was used and a linear Us-Up equation of state. A comparison of the experimental steel plates and the SPHINX results are shown in Figures 3 and 4. The crack patterns are in qualitative agreement, but differences in the details exist. These two dimensional cylindrical calculations show that SPHINX has a problem on the axis symmetry.
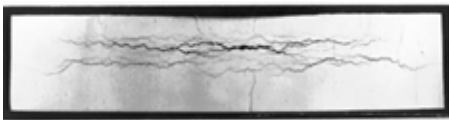

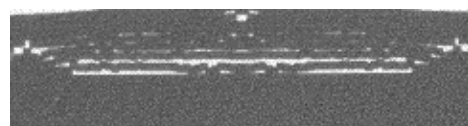
Fig. 3 Experimental crack pattern.

Fig. 4 SPHINX crack pattern.

TUNGSTEN ROD IMPACTING HEAVILY CONFINED ALUMINA

We recently reported on simulations of the crack patterns observed for a short tungsten rod impacting heavily confined alumina[12]. Two dimensional plane strain

calculations with 55,435 SPH particles resulted in crack patterns in qualitative agreement with the experiment. For an equally resolved 3D calculation, about 13 million particles would be required, which is beyond the current capability of the machines we have. The three-dimensional calculations we made with about 300,000 particles gave poor results. The two-dimensional calculations underpredicted the rod depth of penetration. Two-dimensional calculations with 26,638 particles did not even qualitatively match the experimental crack pattern. Details of the calculations and comparisons with the recovered alumina crack patterns are given in reference 12.

CONCLUSIONS AND DISCUSSION

Smooth particle hydrodynamic methods have advantages over more traditional hydrocode mthods for fracture simulations so we have chosen to use this method. A number of fracture models have been implemented into the SPHINX SPH code. Since a hydrocode must be able to accurately simulate a range of experiments before it can be used as a reliable design tool, we have evaluated these models and the code by simulating a number of one-, two-, and three-dimensional impact experiments.

Comparisons between the experiments and the calculations are good in some cases and only qualitatively correct in other cases. Further work is needed in order for the simulations to match details of the experiments. One model and one set of model parameters still cannot adequately simulate all of the experiments we have examined.

We must include a few comments in closing about the tensile instability problem[1] that has yet to be solved. SPHINX and other SPH codes exhibit a numerical instability in regions of tension that tends to bunch particles together. The effects of the tensile instability are somewhat problem dependent and are mitagated by the reduction of the tensile pressure due to the damage, as BA have discussed[3]. Moreover, as we and others have observed, the instability problem can be significantly reduced by including more particles in the SPH sums. We and others are investigating methods to eliminate this problem.

Although further work is needed in both brittle fracture model development and in the codes in order to design devices outside the range of current experience, the codes are very useful in conjuction with experimental results in explaining the experiments and as a to guide future experimental work.

ACKNOWLWDGEMENTS

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